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J. Billingsley

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PROVISIONAL PATENT SPECIFICATION

Invention title: Multi-User Signal Processing

The following statement is a full description of this invention, including the best method of performing it known to us:

chbm M0111129993v1 305001527

Multi-User Signal Processing

The present invention relates to the field of signal processing for telecommunications, and concerns more specifically multi-user signal processing methods and systems. In particular, it relates to a method and system for detecting and decoding multiple signals which occupy overlapping bandwidth and overlapping time resources. It has particular application to narrowband mobile satellite communications systems, which utilise spot beam technology, and where high path loss and limited transmitter power are important factors.

Many efforts have been made in the field of telecommunications to increase the transmission capacity of limited bandwidth, in order to increase the number of simultaneous users able to occupy a common part of the frequency spectrum. In particular, CDMA techniques have been developed, with particular application to wideband radio signals. A number of solutions to the problem of interference suppression have been developed for CDMA systems, including iterative approaches to signal cancellation. This is relatively straightforward, as CDMA systems are inherently interference-resistant, due to the coding employed.

In satellite communications, the re-use of spectrum has been a secondary factor compared with power usage. However, as the number of users increases, an efficient method is needed to distinguish between the different signals. Generally, implementing suitable systems has involved extremely complex solutions and prohibitively high costs. The present invention aims to overcome the disadvantages of the prior art and provide a new method for decoding multiple channels suitable for use in both narrow and wideband applications, and able to re-use frequency between adjacent spot beams in satellite systems.

The present invention provides, in a first aspect, a signal detection method for multi-user signal processing in a TDMA receiver, said method comprising the steps of:

a) receiving a multiple signal transmission on a single TDMA channel or a plurality of closely adjacent TDMA channels;

b) detecting one or more users, and determining transmission channel estimates of user signals comprised in the multiple signal transmission;

c) at least partially decoding a particular input signal representing a first user by utilising the transmission channel estimates;

d) at least partially decoding other signals representing other users by utilising the transmission channel estimates;

e) subtracting weighted representations of said other signals from said multiple signal transmission to produce a soft signal output for said first user;

f) returning to step (b), with said soft signal output being used as said particular input signal, and iteratively repeating the subsequent steps.

Preferably, after step (c), convergence is compared with prescribed convergence criteria, and, if said criteria are satisfied, a hard signal output is produced and said subsequent process steps are discontinued. The method therefore involves a final iteration stage for each user, resulting in an output of the most likely transmitted data for each user signal.

Step (e) is preferably carried out in parallel for signals representing each user.

Preferably, channel estimation is applied on each iteration.

In this way, the signals are iteratively decoded by successive developments of channel estimates, followed by successive cancellation of interfering co-channel signals. On the first iteration no cancellation takes place, as initially there is no a priori estimate of the users' signals.

Step (c) preferably includes the steps of, on each iteration, demodulating said particular signal, comparing the interference on the signal with a prescribed threshold (the interference threshold determined by measuring the noise

equivalence of the multi-user interference), and, if the interference is above this threshold, partially decoding the signal with a single turbo iteration. The signal is then soft modulated for the next iteration. If the interference is below said threshold, multiple turbo iterations are carried out to decode the signal. The number of turbo iterations is preferably controlled by use of statistical analysis, such as EXIT chart analysis. The same process applies for processing signals from other users, step (d).

The method, then, utilises an iterative subtractive approach to interference cancellation. Preferably, on each iteration, all input signals are examined to identify new, previously undetected users. Otherwise, all signals and users are processed in parallel. The residual interference left after cancellation is estimated and the interference threshold based on the residual interference. Cancellation is preferably performed in the order of decreasing signal strength, determined by the step of channel estimation. Each signal is successively demodulated , reconstructed and subtracted from the total received signal.

Preferably, soft subtraction is employed, the weighting for the subtraction being accomplished linearly. In such an approach, the sum of the candidate bit probabilities being equal to one. The interference is estimated based on the partially decoded users and weighted with the channel estimates.

Said receiver may be a power-limited satellite-mounted receiver. The invention is equally applicable to ground based receivers.

The invention provides, in a further aspect, a receiver for use in the above method for multi-user signal processing.

The invention provides, in a further aspect, a method of controlling decoder iterations in a multi-user receiver architecture, comprising use of statistical analysis, such as EXIT chart analysis, or mutual information transfer chart analysis.

The invention provides, in a further aspect, a device for controlling decoder iterations in a multi-user architecture including means for applying statistical analysis, such as EXIT chart analysis, or mutual information transfer chart analysis.

The invention provides a new receiver architecture and technique which functions effectively in situations of multi user interference. The novel approach allows users in adjacent beams of a satellite system to re-use the same frequency.

In broad terms, the concept of the invention provides a way of coordinating users, and can be used to take advantage of spatial, carrier frequency, time and signal polarisation to distinguish between signals from different users at the receiver. When compared with the prior art, it provides a relatively low complexity iterative cancellation technique, as well as a novel system receiver architecture.

The invention allows far greater efficiency in the use of spectrum in satellite systems, allowing more users to simultaneously occupy the same bandwidth. It addresses therefore the increasing problem of bandwidth limitations on radio spectrum in satellite communications systems, set by international agreements. Conversely, as satellite systems with higher power and with greater sensitivity become available, the invention provides the capacity to support greater numbers of users, allowing the limited bandwidth to be used more efficiently to match more effectively the increasing power.

The invention, then, has particular application in narrowband TDMA, in satellite line-of-sight propagation environments, and in power limited systems.

The system of the invention can operate with arbitrary waveforms (in narrow or wideband). Unlike known systems, interference suppression is accomplished via the canceller, rather than using different channel interleavers. In addition, the invention employs iterative cancellation of partially overlapping signals with identical reference sequences (eg unique words - UW).

One aspect of the receiving method concerns the control of the decoder iterations in a multi-user architecture. Statistical metrics, such as an EXIT chart analysis

technique, are used to verify convergence for a prescribed number of decoder iterations.

Brief Description of the Drawings

To illustrate the invention and how it may be put into effect, reference will now be made to the accompanying drawings, which represent a preferred non-limiting embodiment. In the drawings:

Figure 1 diagrammatically illustrates a narrowband multi-user situation;

Figure 2 illustrates the iterative architecture of the system;

Figure 3 depicts a schematic illustration of the interference canceller of the system; and

Figure 4 shows a flow chart depicting the various steps of the iterative cancellation approach.

Detailed Description

In this specification, where a document, act or item of knowledge is referred to or discussed, this reference or discussion is not an admission that the document, act or item of knowledge or any combination thereof was at the priority date part of common general knowledge, or known to be relevant to an attempt to solve any problem with which this specification is concerned.

<u>Multiple User Decoding Strategies</u>

The situation illustrated in Figure 1 includes a plurality of users M_1-M_k communicating with a satellite receiver R on a single TDMA channel, or on two or more closely adjacent channels. The signals received from each respective user include interference from the other users, and suppressing such interference is an essential step in effective receiver performance.

The prior art provides a range of multi-user decoding strategies that provide varying levels of performance and require varying levels of implementation complexity. Depending on the nature and levels of co-channel interference, different types of receivers find different areas of applicability.

Rather than making separate decisions on each user's codeword, a multi-user decoder makes a joint decision on all the users' codewords given the received sequence. The fundamental issue in multi-user decoding is not the amount of spectrum spreading, but the amount of cross-correlation between the users.

The inventors of the present invention have focused on a multi-user detector involving an algorithm that iterates between both joint detection and independent decoding. Such an approach has hitherto not been adopted outside the very different field of CDMA applications. Use of such iteration in narrow-band systems has been postulated in 'Cochannel Interference Suppression with Successive Cancellation in Narrow-Band Systems', H Arslan and K Molnar, IEEE Communications Letters Vol 5, No 2, February 2001, but the performance of such an approach is limited, particularly in instances of acquisition of a weak signal in the presence of a much stronger interfering signal.

The inventors have shown that this application yields performance close to optimal at an acceptable complexity. It is to be noted that joint detection/single user decoding algorithms are of interest both in cases where co-channel interference is severe, and where it is not.

Of importance in multiple-user decoding is the issue of channel estimation. Many multi-user receiver designs either assume or require perfect channel knowledge. The present invention makes no such assumption.

<u>Maximum Likelihood Joint Decoding</u>

The optimal joint decoder minimises the probability of decoder error. This corresponds to the maximum likelihood decoder, which outputs:

$$\hat{c}_1, \hat{c}_2, \ldots, \hat{c}_k = \arg\max \Pr\left(\{y[i]\}_{i=1}^{N} \,|\, c_1, c_2, \ldots, c_k\right)$$

In general this has complexity that increases exponentially with both the number of users and the codeword length. For convolutionally encoded data, joint decoding corresponds to Viterbi decoding on a super-trellis whose states are the concatenations of the individual user states. Because of the small number of users (2-7) under consideration, optimal decoding may appear to be feasible. This will however not be the case, since the use of turbo codes prevents construction of the required super-trellis (in the case of use of turbo codes, the super-trellis becomes too cumbersome to be practical). The concept of optimal decoding is however useful in providing a benchmark against which other methods may be measured.

Interference Cancellation

With careful selection of the users' code rates, or equivalently, their transmit power, successive cancellation of decoded data streams can approach the performance of the optimal decoder. In order for this scheme to be practical, however, the users' powers must be tightly controlled. Thus interference cancellation may be a strong candidate if such power control can be implemented.

Joint Detection, Independent Decoding

Because of the high complexity of optimal joint detection, it is necessary to try to design sub-optimal receivers with lower complexity. The key trade-off is performance versus complexity. One approach to reducing complexity is to separate the problems of detection and decoding. The receiver of the invention makes joint decisions on each received signal (ignoring the constraints due to coding). The resulting signal streams are then independently decoded using regular techniques. Such a strategy results in minimal change to existing architectures.

Multistage Detection

Multi-stage detectors use a process of successive cancellation of the uncoded bits. Cancellation can proceed in serial or parallel. Multistage detectors can be classified as linear or non-linear, according to whether they subtract linear or non-linear functions of the already detected symbols. It can be shown that linear cancellation detectors are simply approximations to the linear filters, such as the decorrelators and MMSE.

Iterative Decoding

We now consider a class of sub-optimal iterative non-linear decoding strategies. The high complexity of optimal decoding arises mainly from the fact that the constraints introduced by coding and channel effects must be processed jointly for all users. In contrast, iterative non-linear methods aim to iteratively reconstruct from the channel output each user's transmitted waveform using marginal posterior distributions. Code multiple-access systems can be considered as concatenated coded systems. The received signal is constrained both by the individual channel codes and by the structure of the multiple-access channel. The basic principle behind the design of iterative multi-user receivers is to separate the problem of inter-user dependence (due to the multiple-access channel) and time dependence (due to channel coding and inter-symbol interference).

A joint detection module calculates posterior distributions on the data incorporating multiple-accessing constraints, but ignoring coding constraint. The posteriors are used as priors by individual decoders for each user, which independently produce posteriors on the user data taking into account only the constraints due to the codes, and ignoring the multi-accessing constraints. These posteriors are then fed back to the joint detection module, and so on. The receivers are non-linear due to the incorporation of decoders in the decision process, and due to the fact that the joint detection module may itself be a non-linear device. In particular, the reconstruction of one particular user's waveform from the common channel output is obtained by *cancelling* in a non-linear way

the estimated contribution of all other users. Such a technique results in particularly low complexity implementations.

One of the main challenges in multi-user receiver design is in the size of the signalling constellation. Indeed, even if the number of interfering users is small, the size of the constellation appears to be the limiting factor for applying optimal joint detection techniques. In such cases, the cancellation-based scheme is clearly preferable to methods whose complexity is dominated by a term exponential in both the number of bits transmitted per symbol and the number of users. In fact, for a D-ary constellation and K users, the complexity of those schemes is $O(D^k)$. Results show that the low-complexity iterative cancellation approach can be applied successfully to single user turbo-equalisation for 16- and 64-QAM. Another point of note is that any non-linear iterative decoding scheme requires independent interleaving of each user's data (usually taking place after the encoder). It has been shown that the presence of an interleaver is a necessary condition for any successive cancellation technique to converge. Another crucial point to be considered in this problem is that of channel estimation. The inventors have shown that including channel estimation inside the iteration can yield significant performance gains. In this way, each user's channel estimate is improved as the data estimates improve.

<u>Iterative Multi-User Decoding</u>

We now focus on the multi-user receiver architecture according to the present invention. The architecture is flexible enough to provide a range of solutions of different complexity for different applications. Furthermore, there are a number of optional features that can be incorporated, depending upon the changes permitted to the system requirements.

Broadly speaking, the system of the invention achieves interference suppression by first detecting and decoding the received signals in multiple stages, and then cancelling the unwanted signals. This process is carried out iteratively, and this approach is specific to interferers that are asynchronous to the wanted signal.

Figure 2 shows an architecture suitable for decoding multiple users, signals y_1, y_2, ... y_k, in accordance with the present invention. Performance tests have shown this architecture to yield near optimal performance (approaching single user) under certain conditions and linear increase in complexity with increasing numbers of users. The architecture consists of a feedback structure comprising an interference canceller, channel estimator, soft demodulator, soft output decoder, soft modulator and estimated multi-user channel. The receiver comprises multiple parallel processor arms as shown, each receiver arm serving to converge on a respective user (see below). Broadly, the principle of operation is to iteratively improve soft estimates of multiple users simultaneously, where the users' signals occupy overlapping channel time/bandwidth resources. With no a priori knowledge of users, the number of active receiver arms can vary through successive iterations, as weaker signals become apparent through progressive interference suppression.

The interference canceller block takes multiple received signals, acquires signal lock (acquisition), and filters to reduce the effects of noise. On subsequent iterations, the estimated multi-user channel vectors are cancelled from the received signals to reduce interference. Effectively, the interference canceller removes multiple access interference with respect to each possible user. Acquisition occurs through joint detection of each user from all signals.

As mentioned above, for each user there is a processing arm consisting of soft demodulator, soft output decoder (partial decoding), and soft modulator. This provides a soft weighted estimate of each user's signal. The partial soft input/soft output decoder allows control over the use of time dependent signal constraints from zero to complete. This is accomplished (see below) by means of setting the number of turbo decoder iterations between 0 and a maximum value, which avoids the problem of false locking onto a combination of users resulting from incomplete interference cancellation.

The channel estimator provides estimates of the radio link parameters necessary for demodulation, e.g. timing, frequency, amplitude and phase of a coherent

demodulator. It provides estimation of the relative level of each user from all signals.

The estimated multi-user channel block combines the soft modulated single user vectors to generate estimates of each of the received signals, including data values and radio link effects (except additive noise). These are then used by the interference canceller to cancel interference from the received signals at each iteration of the algorithm.

On the last iteration hard decisions are output to reflect the most likely transmitted data bits for each user, thus a final decision is made on the most likely transmitted data for each user.

The particular embodiment of the invention developed by the inventors and depicted in the figures involves an iterative multi-user device for multi-user decoding for narrow-band satellite services. Let us consider the general structure of the proposed non-linear iterative multi-user detector of the invention. We denote by $b_k[i]$ the uncoded sequence of bits at the input of the user *k's* turbo encoder. The coded sequence of bits is denoted by $b_k[i]$ and $b_k[i]$ is the sequence of modulated symbols taken from a 16-QAM constellation. The output of the satellite channel may be modelled as:

$$\bar{y}[i] = \bar{y}[i] + \bar{x}[i]$$

The vector channel output $y[i]$, is then processed iteratively by the following devices:

1. **Interference Cancellor**: This device produces soft estimates of the coded and modulated symbols $x_k(i)$. Note that this is in fact the key device in the system since it aims at effectively separating the users based on each user's marginal a–posteriori probability distribution. At the first iteration, there is of course no available information for approximating these marginal probabilities.

2. **Soft Demodulator:** Produces the a-posteriori probabilities $PR(d_k[i] | x\hat{}_k[i]$ for each symbol taken from the QAM constellation (this component is already required for single user soft-decision turbo decoding).

3. **Soft turbo decoder:** Refines the a-posteriori probabilities of the coded bits by taking into account the knowledge of the turbo code. The signals are only partially decoded during the first few receiver iterations in order to prevent the estimated signal from locking in to an incorrect value (ie converging to a false lock, an incorrect codeword nearest the transmitted signal - plus noise, plus interference). The partial decoding is controlled by changing the number of turbo-decoder iterations, where the first few receiver iterations have few decoder iterations and the final few iterations contain up to ten turbo-iterations. In this way, the level of partial decoding is progressively increased by changing the number of turbo decoder iterations from 0 to the maximum (10) on the final iteration. At each stage, the number of turbo iterations to be applied is determined by pseudo-analytical methods (statistical techniques) such as 'EXIT' (Extrinsic Information Transfer) Chart analysis, mutual information transfer chart analysis, or experimental optimisation.

   The partial decoder control is selected in order to ensure convergence with minimum complexity. This results in a partial decoder profile. Several profiles are computed offline for different scenarios of number of users and relative interference. The receiver identifies the closest scenario and employs the appropriate partial decoder profile. EXIT chart analysis is discussed further in 'Convergence Behavior of Iteratively Decoded Parallel Concatenated Codes'; Stephan ten Brink; IEEE Transactions on Communications; Vol. 49, No. 10; pp 1727; October 2001. The EXIT chart analysis can be viewed as a software gauge attached to the soft outputs of the decoder, enabling determination of convergence by determining the number of turbo iterations.

4. **Soft modulator:** Produces the conditional expectation $E[x_k[i]]$ of the coded and modulation symbols (according to the posteriors calculated by the

decoders). These average symbols are further fed back to the multi-user detector for the next iteration.

5. **Channel estimator:** Updates the channel estimate for each user. Note that this device takes as input the output of the soft modulator and feeds the multi-user detector device. This shows that this device is one of the key points for convergence of such an iterative system. Note that if enough training symbols are present, or at high enough signal to noise ratios, the channel estimates from the initial iteration may be sufficiently accurate.

Figure 3 depicts the operation of the cancelling module. This does not operate on the first iteration, as on the first iteration the interference estimate is zero and no cancellation occurs. For subsequent iterations, the cancelling module is a non-linear cancellation device where the soft estimate $x^{\wedge}_{k}[i]$ of the coded and modulated symbol for user k is obtained by subtracting from $y[i]$, the average contribution of other users (where the average is calculated according to the posterior distributions from the previous iteration). Note that in order to cancel each user's contribution to the received vector, estimates of the users' channels are required.

Prior approaches to iterative channel estimation approaches have employed processing steps such as hyperbolic tangent devices, which are used to control how much of the estimated interference is actually used in the cancellation at each iteration. Such methods require an estimation of absolute power to be made at the antenna, as without such prior knowledge the algorithm may be ineffective. In contrast, in the present invention this soft decision step is implemented by way of the linear device referred to above. In this approach to the weighting, the sum of the candidate bit probabilities is equal to one. This contrasts with a device such as the hyperbolic tangent device referred to above, wherein this sum total is artificially reduced to compensate for the inaccuracy of the estimated signal. As the method of the invention does not involve locking into the signal on initial receiver iterations, it is not required to compensate for initial inaccuracies.

Additionally, prior approaches have generally applied a single channel estimation via a training sequence, using that channel estimation for all packets and all iteration steps, and have generally used a known training sequence for each TDMA burst. The algorithm of the present invention carries out channel estimation on a packet-by-packet basis, for each iteration, and using a reference sequence (eg a UW) present in the packet. This updating of the channel estimation on each pass can lead to significant improvement in receiver performance.

The operation of the canceller is as follows:

Field $y_1, y_2, \ldots, y_K$ are received signals

$$R_p = \sum_{i=1:K\backslash i\neq p} \rho_{pi}\hat{z}_i$$

- $p = 1, 2, \ldots, K$
- z_i is the output of the i^{th} soft modulator after reapplying the channel parameters.
- ρ_{pi} – relative interference value of the i^{th} user interfering with user p.

$$\hat{x}_p = y_p - R_p$$

Turning to Figure 4, the steps of cancellation and turbo decoding on a receiver processing arm are schematically illustrated. The flow chart makes clear that on the first iteration the canceller does not operate. The demodulated signal is checked on each iteration by comparing the interference on a signal with a prescribed threshold, and, if the interference is above this threshold, the signal is partially decoded with a single turbo iteration. If the interference is below this threshold, multiple turbo iterations are carried out to decode the signal. This switching between a single turbo iteration and more turbo iterations is important in increasing the performance of the invention. Different techniques can be used for estimating the interference threshold, including measuring the received signal-to-noise ratio, and performing off-line calibration. Further, different techniques

can be used for determining the optimal number of turbo iterations. This can be done by analysing the EXIT charts, or by making calibration measurements. There is, of course, a trade-off between complexity and performance of the different techniques.

The convergence properties of the method of the present invention have been analysed by the inventors. This analysis has showed that the receiver architecture, when combined with appropriate probabilistic component algorithms, allows very high spectral efficiencies to be achieved. Experiments have demonstrated spectral efficiency up to 10 bits per second per Hertz *(bps/Hz)* compared with conventional transmitter receivers that achieve 1-2 *bps/Hz*, with only a small increase in transmitter power (less than 1dB). Studies of the effects of the system of the invention on acquisition (coarse time and frequency estimation) have demonstrated that this approach provides particular advantages when acquiring a weak user signal in the presence of a much stronger interfering signal.

The technique described above involves the strongest users (signal) on each arm of the receiver being detected, and other interfering users cancelled from it with the appropriate weighting. Each user's signal is therefore taken from only one Rx arm, this approach being referred to as 'selective combining'. It is to be noted that the invention can also be applied to other post-detection combining techniques such as 'maximal ratio combining', where the contributions from each user are combined for each of the receiver arms. Combining techniques are further described in 'Mobile Communications Engineering, Theory and Applications', W. C. Y. Lee, McGraw Hill, 1997.

DSpace Pty Ltd 14 June 2002

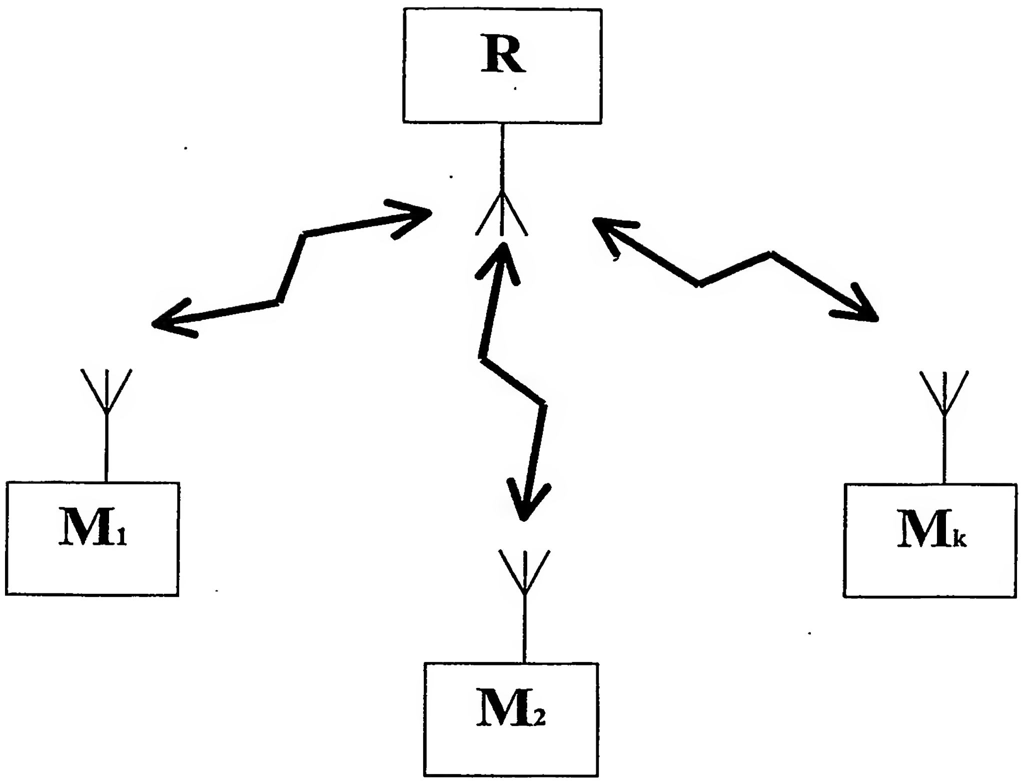
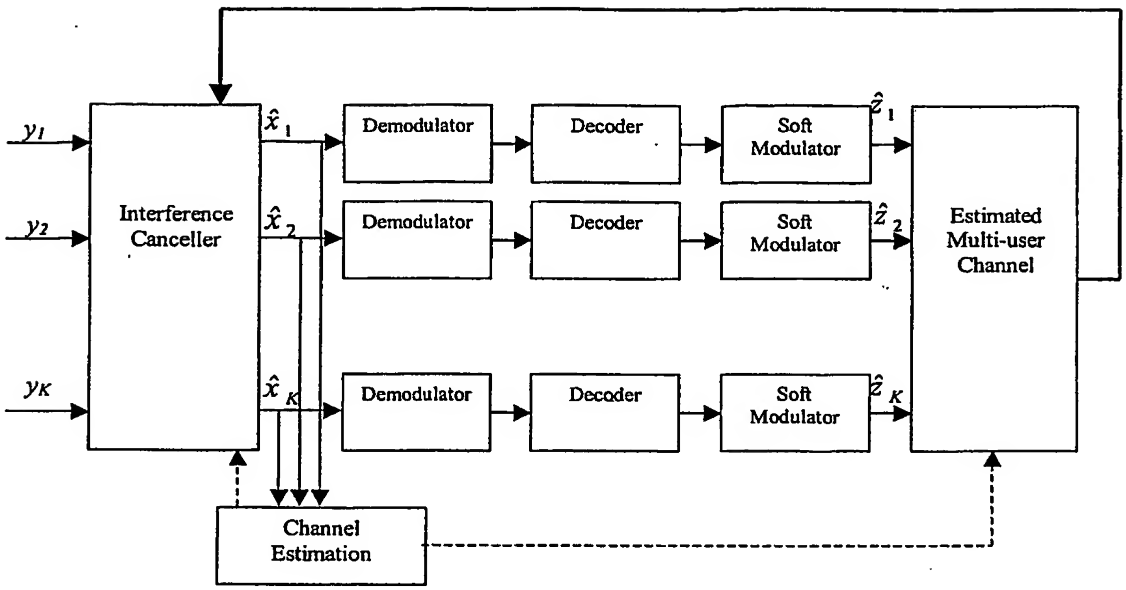


Figure 1



y_1
y_2
y_K
Interference Canceller
$\hat{x}_1$
$\hat{x}_2$
$\hat{x}_K$
Demodulator
Demodulator
Demodulator
Decoder
Decoder
Decoder
Soft Modulator
Soft Modulator
Soft Modulator
$\hat{z}_1$
$\hat{z}_2$
$\hat{z}_K$
Estimated Multi-user Channel
Channel Estimation

Figure 2

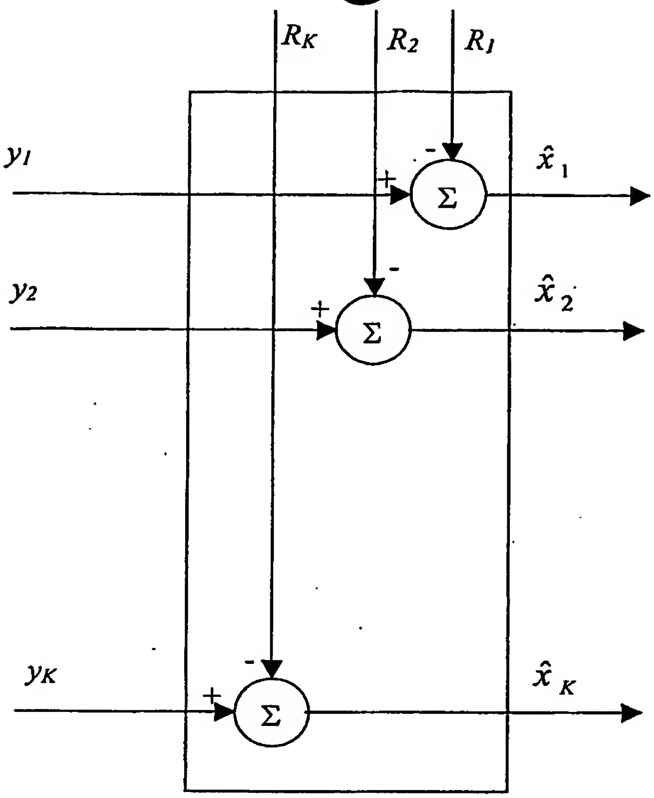


Figure 3

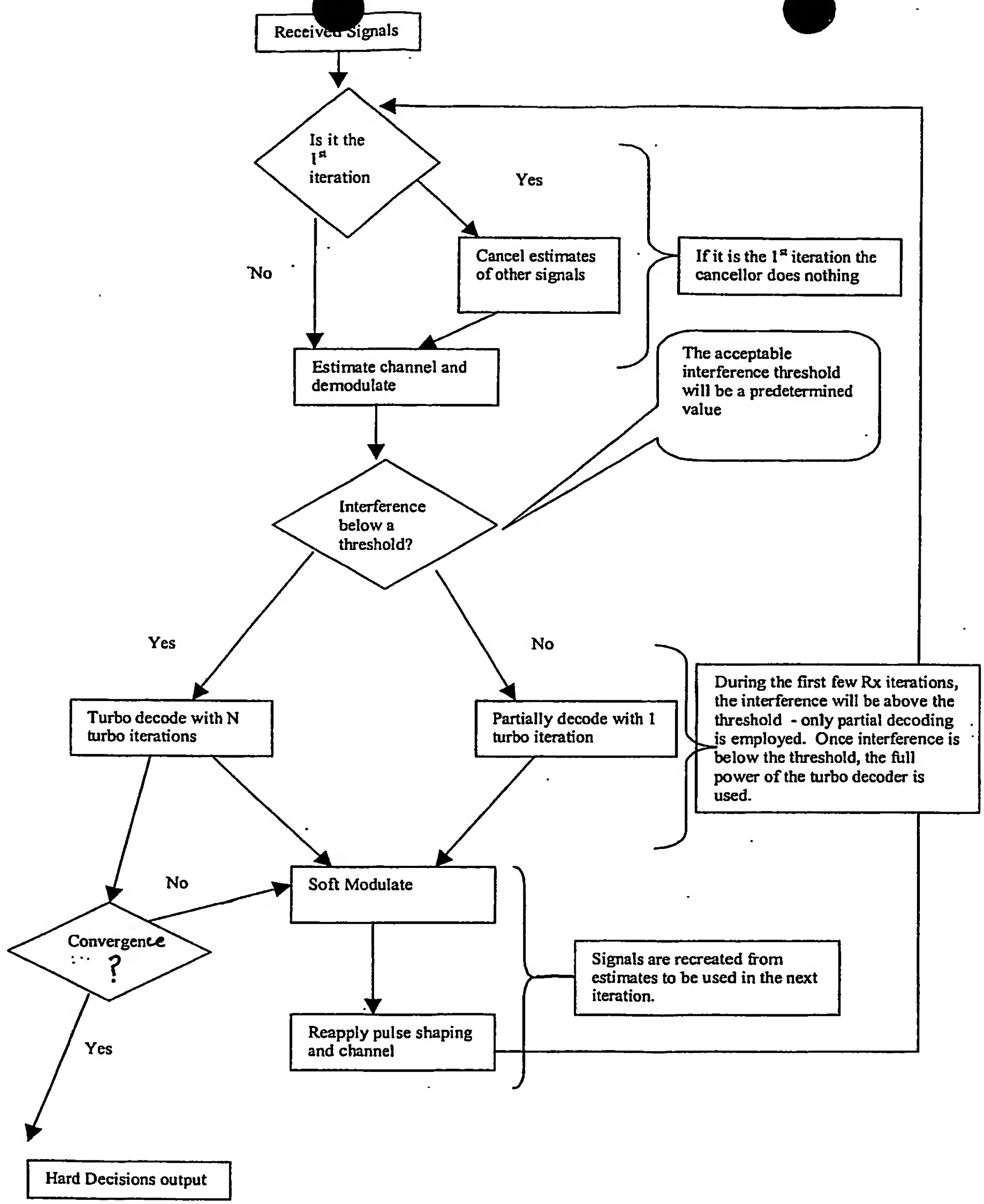

Received Signals
Is it the 1st iteration
Yes
No
Cancel estimates of other signals
If it is the 1st iteration the cancellor does nothing
Estimate channel and demodulate
The acceptable interference threshold will be a predetermined value
Interference below a threshold?
Yes
No
Turbo decode with N turbo iterations
Partially decode with 1 turbo iteration
During the first few Rx iterations, the interference will be above the threshold - only partial decoding is employed. Once interference is below the threshold, the full power of the turbo decoder is used.
No
Soft Modulate
Convergence ?
Signals are recreated from estimates to be used in the next iteration.
Reapply pulse shaping and channel
Yes
Hard Decisions output

Figure 4